Hydrodynamics of Palu Bay during the Event of 2018 Palu Earthquake and Tsunami

Hidrodinamika Teluk Palu pada Gempabumi dan Tsunami Tahun 2018

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ABSTRACT: The devastation of coastal area in Palu Bay few minutes after the September 28th, 2018 Sulawesi earthquake showed high variation of tsunami arrival time as well as the tsunami run-up and inundation. Recent findings showed that both local submarine landslides and the normal-slip components inside the Palu Bay may contribute to the generation of tsunami. However, the fact that the event occurred during high tide, the hydrodynamic characteristics of this narrow bay and their role in the dynamics of the generated of tsunami were unknown. Hydrodynamics simulation (Mike21-flow model) using the latest available bathymetry field data (the 2018 deep water of the Indonesian navy data and 2015 shallow water of the BIG data) was conducted to investigate the variation of sea levels and tidal currents within the bay during the event of earthquake and tsunami or within the first 8 minutes timeframe. Results showed that significant increase of water elevation up to 6 cm and current velocity up to 1 cm/s directed towards the city of Palu were observed that may contribute to the dynamics of the tsunami e.g. the speed of tsunami arrival time and the transformation of tsunami. Therefore, considering that multiple tsunami arrivals were in few minutes after the earthquakes, the hydrodynamics of Palu Bay during the event should also be considered in future tsunami simulation scenarios.

Keywords: Palu, Tsunami, Earthquake, Tides, Hydrodynamic

ABSTRAK: *Kerusakan kawasan pesisir di Teluk Palu beberapa menit setelah gempa bumi 28 September 2018 menunjukkan variasi yang sangat beragam pada tinggi tsunami, limpasan, waktu tiba dan jarak rendaman. Penemuan terkini memperlihatkan bahwa longsoran bawah laut dan meknisme patahan normal kemungkinan besar berkontribusi pada terjadinya tsunami. Namun, fakta bahwa kejadian tsunami terjadi saat kondisi pasang tinggi, karakteristik hidrodinamika dari teluk yang sempit ini dan perannya dalam tsunami yang terjadi belum diketahui. Simulasi hidrodinamika (Mike 21 – flow model) berdasarkan data batimetri terkini (Dinas hidroosenografi TNI AL dan BIG) menginvestigasi variasi muka air dan arus pasang surut saat kejadian gempa bumi dan tsunami atau dalam kurun waktu 8 menit setelah gempa utama. Hasil simulasi memperlihatkan peningkatan tinggi muka air yang cukup signifikan hingga 6 cm dan kecepatan arus hingga 1 cm/s menuju kota Palu yang dapat berkontribusi pada dinamika tsunami di Teluk Palu (waktu tiba dan transformasi tsunami). Oleh karena itu, dengan mempertimbangkan kedatangan tsunami yang terjadi dalam beberapa menit, hidrodinamika Teluk Palu perlu dipertimbangkan dalam skenario pemodelan tsunami di masa yang akan datang.*

Kata kunci: *Palu, Tsunami, Gempa bumi, Pasut, Hidrodinamika*

INTRODUCTION

On September 28, 2018 (10:02:45 UTC or 18:02:45 WITA, Central Indonesian Time), Palu was shaken by Mw 7.5 strike-slip earthquake and in few minutes later followed by destructive tsunami destroying the coastal city with more than 2000 casualties (BNPB, 2018). The epicenter of the earthquake was in the north of Palu Bay (0.256°S and 119.846°E), but the 2018 Palu Tsunami was clearly generated inside the Palu Bay (ITST, 2018, Omira, *et al.*, 2019, Syamsidik *et al.*, 2018) (Fig. 1a and 1b). Submarine landslide was suggested to be the main tsunami generator inside the bay while the possibility of normal fault mechanisms inside the bay remain challenging due to lack of data prior the event (Liu *et al.*, 2020) (Fig. 1c). Meanwhile, videos from social media and CCTV records played important role in determining the characteristics of the tsunami,

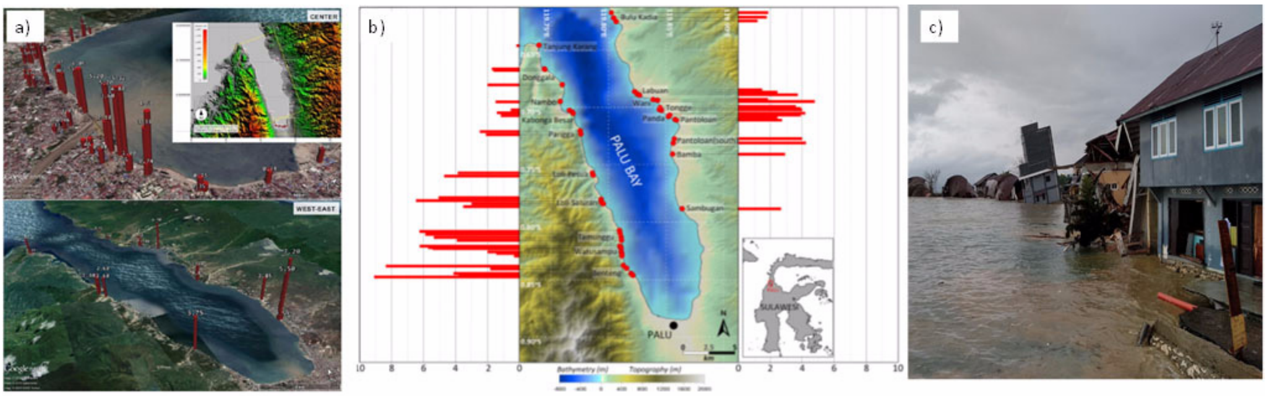


Figure 1. a) Tsunami inundation in Palu (Syamsidik et. al., 2019), b) Tsunami run-up in Palu (Omira *et al.*, 2019), c) Evidence of submarine landslide in Muara Village, Donggala (taken on 08.11.2018).

especially the arrival time, tsunami flow/magnitude and the impact to the infrastructures (Carvajal, *et al.*, 2019, Husrin, *et al.*, 2018). Many field measurements were conducted to identify the characteristic of tsunami run up and inundation within the Palu Bay (ITST, 2018, Omira, *et al.*, 2019, Syamsidik *et al.*, 2018) (Fig. 1a and 1b). Based on the obtained field data, attempts to model tsunami generation and propagation were made to mimic the impact of tsunami along the coastline of the bay (Palu and Donggala) (Gusman *et al*, 2019, Nakata *et al.*, 2020). Latest findings based on the latest measurement of coastal bathymetry showed that considering only landslides may still not be enough to simulate all processes occurring inside the bay (Liu *et al.*, 2020). Normal faults located in the middle of the bay should also be considered for the possible generation of tsunami. However, deep water bathymetry data prior the event was not available, making a more accurate analysis was not possible because the fault parameters to generate the tsunami inside the bay are unknown (Gusman *et al.*, 2019, Ulrich *et al.*, 2019 and Nakata *et al.*, 2020).

Hydrodynamics are very important and in some cases could significantly influence the characteristics of tsunami magnitudes and arrivals (Kowalik & Proshutinsky, 2010, Kalmbacher & Hill, 2015, Shelby *et al.*, 2016 and Wrinckler *et al.*, 2017). Considering the narrow shape of the bay and wide opening in the north of the bay (~ 30 km long and ~5 km wide), the hydrodynamic characteristic of Palu Bay so far was not considered in the analyses for tsunami generation (Gusman *et al.*, 2019, Ulrich *et al.*, 2019 and Nakata *et al.*, 2020). It was reported that the tsunami event occurred during high tide as shown from the Pantoloan tide gauge record, the only tide gauge available for the validation of all tsunami model inside the bay (ITST, 2018, Omira, *et al.*, 2019). There was no information about water levels near the city of Palu. Because of very short tsunami travel times (3-5 minutes), the variation of water levels in Palu Bay is needed for additional consideration in adjusting the generated tsunami characteristics in Palu Bay. Therefore, the objective of this paper is to understand the hydrodynamic of Palu Bay during the event, especially in the time frame of the first 8 minutes after the main earthquake.

METHODOLOGY

A flowchart of the current study is shown in Figure 2. The main task is conducting hydrodynamic simulation based on available data and further analyses to see the relationship of the hydrodynamic model and the characteristics of the tsunami. The hydrodynamic simulation was conducted using Mike-21 hydrodynamic flow model, commonly used for hydrodynamic simulation of coastal areas such as bays and estuaries. The shallow water equations in the model are governed by the conservation of mass and

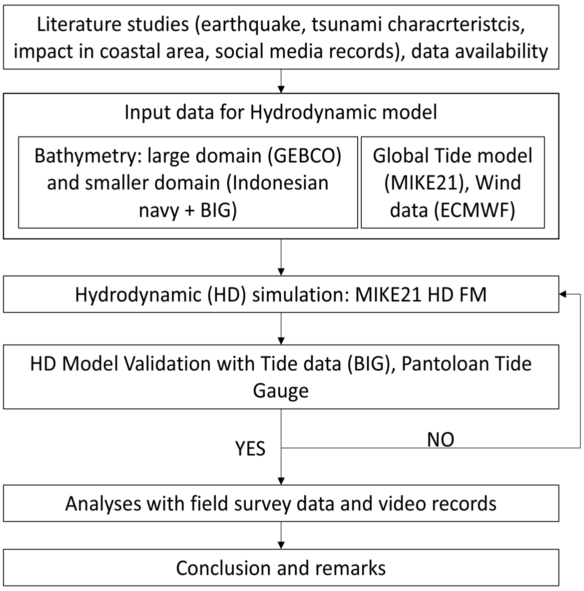


Figure 2. The flow chat of current study

momentum equations (the Danish Hydraulic Institute, DHI, 2011). Cell- finite volume method was used in the numerical scheme for spatial discretisation (triangular grid cells). Details about the model and examples of similar hydrodynamic application in the bay can be found in DHI (2011), Wisha *et al.*, (2015), and Wisha et.al., (2016). The model in the current study requires input data such as the bathymetry, tidal elevations in the boundary conditions and wind as an important additional factor.

The hydrodynamic simulation domain was divided into two domains, the large domain (part of Makassar Strait) and the smaller domain (Palu Bay). Bathymetry data from GEBCO with a resolution of 900 m was used (www.gebco.net) for the large domain simulation. The bathymetry data for smaller domain (Palu Bay) consists of two parts, the deep water and the shallow water. The deep-water data was obtained from the Indonesian navy which was conducted post-tsunami survey using multi-beam sonar two weeks after the earthquake. The bathymetry data in deep water has a resolution of 10 m and it is similar to the deep-water data as presented by Frederik *et al.*, (2019). The shallow water bathymetry data was obtained from the Indonesian Geospatial Agency or BIG. BIG provided different bathymetry data from 2014, 2015, and 2017 in its website (http://batnas.big.go.id/). For the current study, the data from year 2014 was used due to its consistency with the latest deep-water data. Both bathymetry data were combined, and the final resolution used in the simulation was 50 m (Figure 3).

Table 1: Numerical simulation parameters

Parameters	Applied in simulation
Time Simulation	Number of time step = 720
	Time step interval = 3600 s
	Start & stop simulation date: 1/9/2018; 12:00 am – 30/9/2018; 12:00 am
Mesh Boundary	Bathymetry = Bathymetry of survey result combined by GEBCO, DISHIDROS (2018) and BIG bathymetry data (2014)
Flood and Dry	Drying depth = 0.005 m
	Flooding depth = 0.05m
	Wetting depth = 0.1 m
Boundary Condition	Tide Forecasting with coordinates : 1. Long : 119.7564010, Lat : -0.43349999 2. Long : 119.5518035, Lat : -0.43389999 3. Long : 119.5518035, Lat : -0.43389999 4. Long : 119.5408020, Lat : -0.87459999
	Type = Flather condition Level → Format = Varying in time and along boundary

The tidal elevation for the boundary condition in open waters was obtained from the in-built global tide model inside the MIKE-21 (DHI, 2011). Wind data with 6 hours interval and resolution of 0.125° x 0.125° was obtained from and applied in the model varying in time. The data from Pantoloan tide gauge station was used for the validation of the model with simulation time for 30 days. Deeper analyses were conducted for smaller domain (Palu Bay), especially for the first 8 minutes after the earthquake or during the tsunami. To enrich the analyses, video records from social media and CCTV records were also analysed to understand the characteristics of tsunami flow in coastal area.

RESULTS

The simulation was successfully conducted for a month or from September 1st - 30th, 2018. The obtained water elevation from the simulation was validated with the data from the tide station in Pantoloan (Figure 4). The model shows a high correlation value compared with the field data (0.97). Based on the characteristics of tidal constituents (O1, K1, S2 and M2), the tidal type of Palu bay is mix semi-diurnal with the Formzhal value F=0.29 or experiencing two-time high tide and two-time low tide in a day (24 hours). The tidal range during the simulation was about ~2 m (1.93 m). Figure. 4 shows that the start of the tsunami event on September 28th, 2019 (18:02 WITA or 10:02 UTC) occurred during tidal condition towards high tide or not at the peak of high tide condition. At the peak of high tide condition, smaller water level oscillation still could be observed.

To understand the characteristics of tidal condition in the bay, each of the tidal phases was investigated. Figure 5 shows four tidal phases extracted from the simulation on September 9th-10th, 2018 or during the phase of spring tide: high tide, towards low tide, low tide and towards high tide conditions. Figure 5a shows the condition during high tide (spring tide) on September 9th, 2018 at 21:59 WITA (Central Indonesian Time) with the highest elevation was 1.106 m above MSL. Inside the bay, the highest elevations was 1.0272 m until 1.0383 m (above MSL) near the mouth of the bay. The currents were observed to be weak inside the bay. About 3 hours later or on September 10th, 2018 at 00:59 WITA, the condition was towards low tide with tidal elevation at 0.2678 m - 0.2728 m (above MSL) inside the bay. Higher elevation in wider area inside the bay was observed compared to the condition during high tide. The elevation in the city of Palu was lower compared to other area inside the bay. The current was stronger, and the direction was generally towards Northwest or leaving out of the bay. On September 10th, 2018 at 04:59 WITA, the tide was at

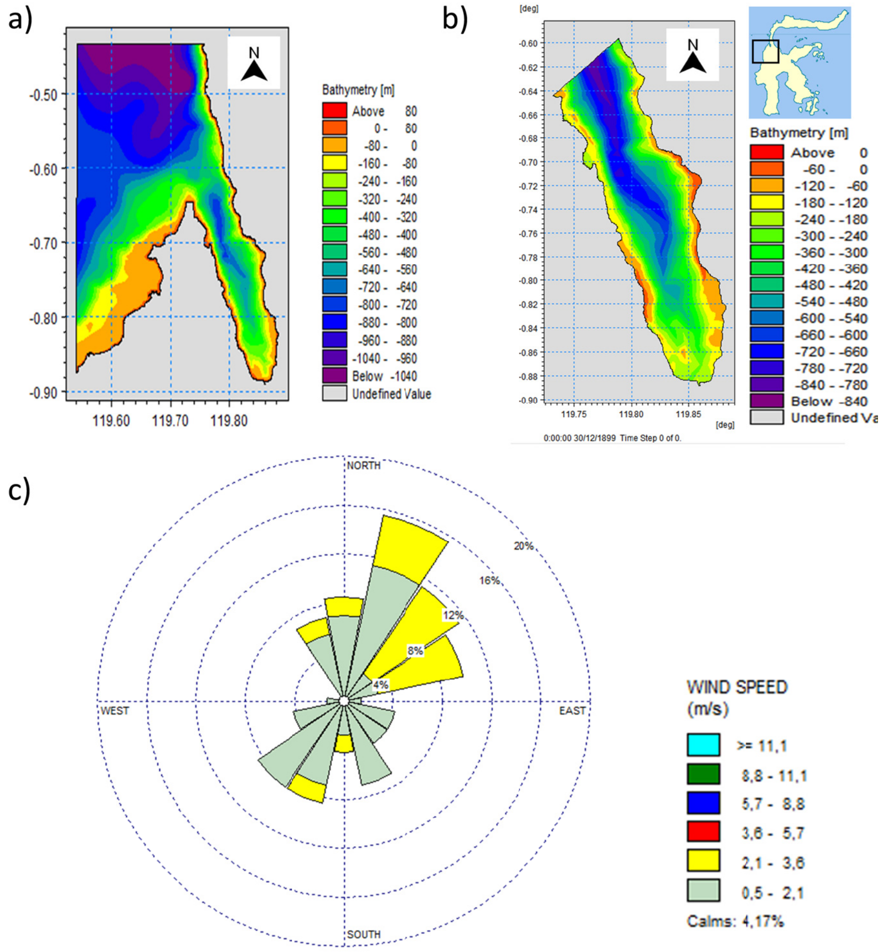


Figure 3. Bathymetry data used in the simualtion a) the large domain (part of Makkasar Strait) and b) the smaller domain (Palu bay), c) wind data from European Centre for Medium-Range Weather Forecasts (ECMWF) on September 2018

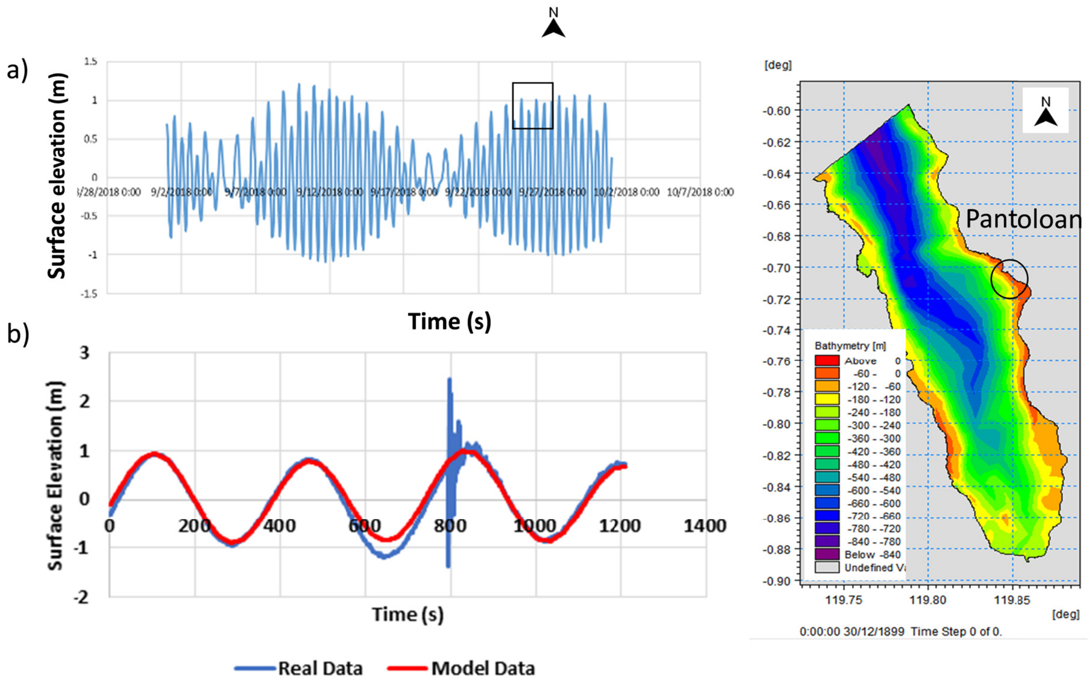


Figure 4. Simulation results at Pantoloan, a) tide model in September 2018, b) validation with field data in Pantoloan during the event

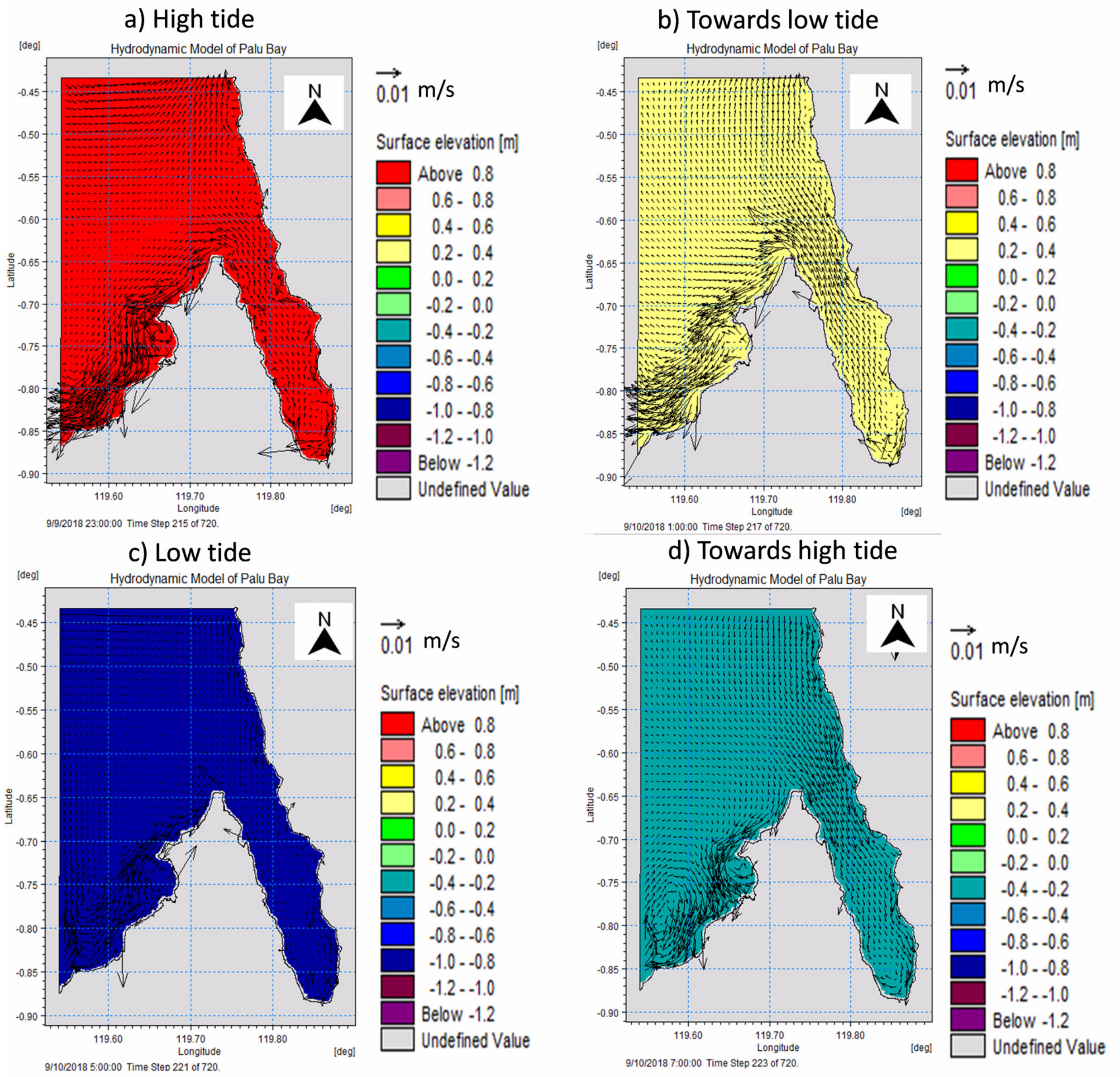


Figure 5. Tidal phases in Palu Bay on September 9th-10th, 2018 or during spring tide, a) During high tide, b) Towards low tide, c) Low tide and d) towards high tide).

low water level condition with elevation -0.8867 m until -0.8832 m below MSL. The current was observed to be weak without dominant directions. The elevation around the city of Palu was generally higher compared to the middle of the bay. About two and a half hour later or on September 10th, 2018 at 07:30 WITA, the tidal condition was towards high tide with the elevation variation ranging from -0.2647 m until -0.2646 m below the MSL. During this phase, the current rushed in towards the bay because of higher elevation outside the bay. The water elevation in the city of Palu was higher compared to the surrounding area.

The characteristics of the flow during neap tide was similar as the conditions during spring tide except for the magnitude (elevations and currents) which is lower. Figure. 6 (a,b,c and d) shows the characteristics of tidal current in Palu Bay during neap tide. Similar characteristics observed for both neap and spring tide are the variation of elevation and current inside the bay especially during low tide and towards high tide where isolines showing the gradation of water elevation were clearly visible inside the bay.

DISCUSSION

The main concern of the current study is to investigate the hydrodynamic condition during the event of the earthquake and tsunami 2018. The main earthquake occurred on September 28th, 2018 at

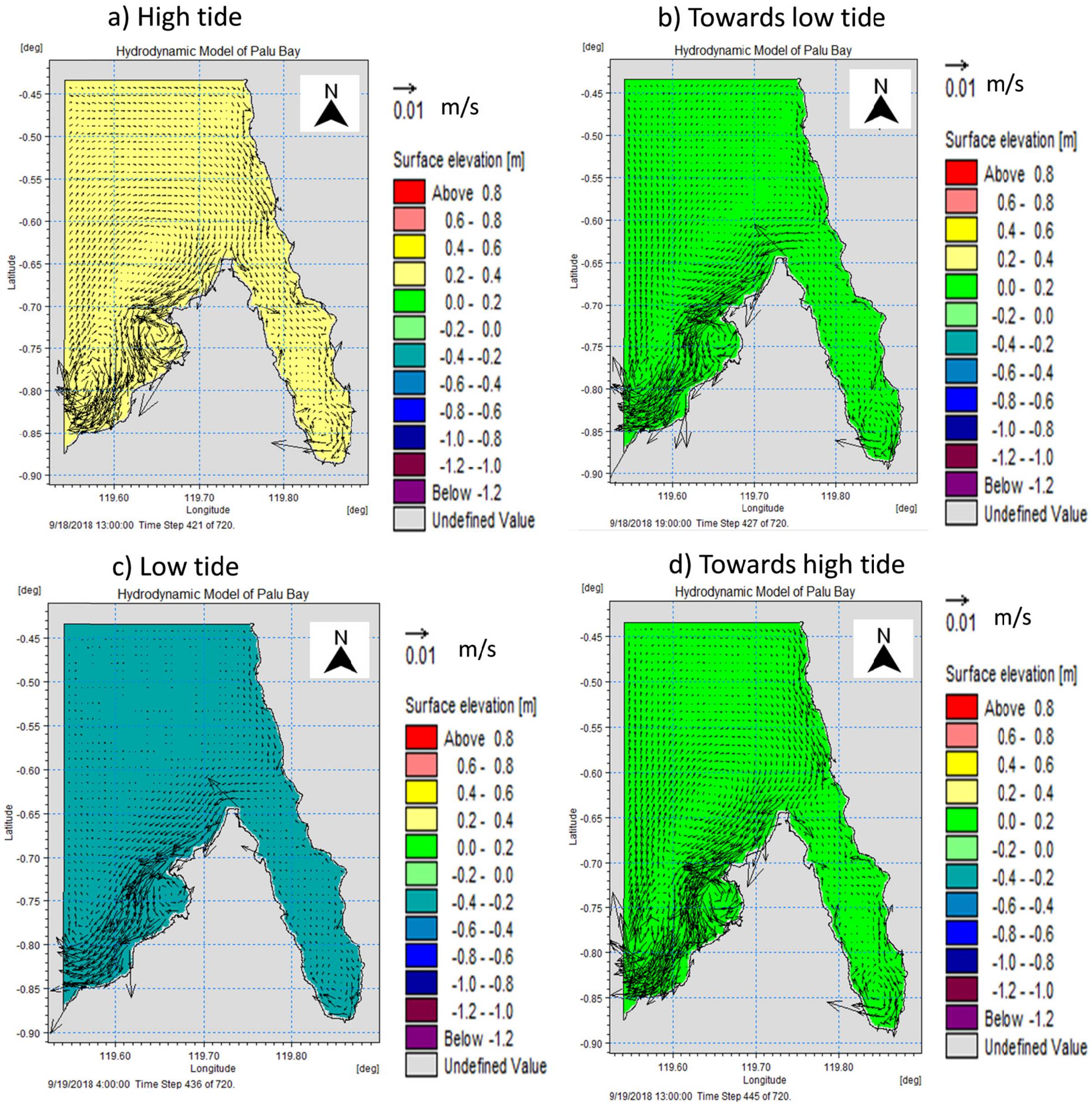
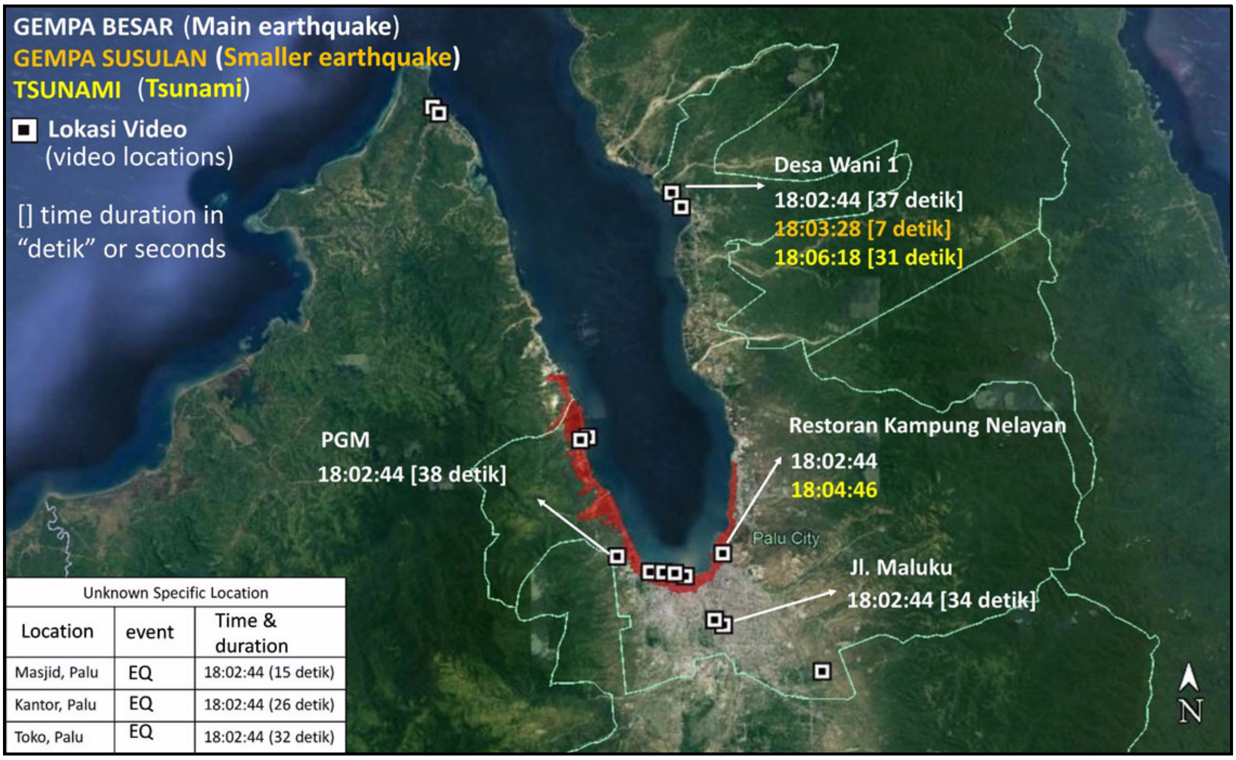


Figure 6. Tidal phases in Palu Bay on September 18th-19th, 2018 or during neap tide, a) high tide, b) Towards low tide, c) Low tide and d) towards high tide.

10:02:45 UTC or 18:02:45 WITA or Central Indonesian Time. Social media and CCTV records showed that tsunami arrivals in the shoreline of Palu and Donggala varied from place to place. However, most of them showed that the first wave arrived less than 4 minutes. We investigate 48 video records and found that only 4 (four) videos provide accurate time stamps. The time stamp in each video records are different but it is understood that the large earthquake had started at the same time. Therefore, the time stamp should be first adjusted to the official reference time reported by the Indonesian Agency of Meteorology, Climatology and Geophysics or BMKG (BMKG, 2018) in order to get the starting point and to be comparable with other locations for further analysis. Based on this information, Figure. 7 shows the characteristics of the earthquake and tsunami recorded by the social media and CCTV records. It is identified that the duration of the main earthquake lasted for more than 30 seconds followed by smaller and shorter earthquakes that might be related to the subaerial or submarine landslides. From the records, we learnt that in Desa Wani 1, tsunami arrived at the house just 3 minutes and 53 seconds. In Kampung Nelayan restaurant, tsunami arrived even faster at 2 minute and 58 seconds. The record in Desa Wani 1 also shows that the tsunami exists



Unknown Specific Location

Location	event	Time & duration
Masjid, Palu	EQ	18:02:44 (15 detik)
Kantor, Palu	EQ	18:02:44 (26 detik)
Toko, Palu	EQ	18:02:44 (32 detik)

Figure 7. Time stamps found in video records (normalised time to the official time of BMKG) (Modified from Husrin *et. al.*, 2018)

for about 31 seconds. The findings were generally in line with similar analyses conducted by Carvajal *et al.*, (2019). Considering large distance between the two locations, different tsunami time arrivals for both Desa Wani 1 and Kampung Nelayan might be related to different tsunami sources (Carvajal *et al.*, 2019, Liu, *et al.*, 2020).

Based on the tide gauge data in Pantoloan, the first tsunami was identified in the first 8 minutes after the earthquake (Figure. 4b). From the figure, the first tsunami wave arrived in Pantoloan Port at 18:07 WITA (10:07 UTC) followed by the wave trough at 18:08 WITA (10.08 UTC) and the wave crest at 18:10 WITA (10:10 UTC) (Widiyanto *et al.*, 2019). This means that the first 8 minutes was critical for determination of tsunami arrival times at different locations considering that the tsunami arrival times were in fact only in few minutes or almost intantenous (Carvajal *et al.*, 2019).

Figure. 8 and 9 show an overview of different tidal elevations in Palu Bay from 18:00 – 18:10 WITA (Central Indonesian Time) or 10:00 – 10:10 UTC extracted from the smaller domain of the hydrodynamic model. We included 18:00 WITA (10:00 UTC) for reference time representing a condition before the earthquake. The points in the middle of the bay are represented the extracted elevation value for each time frame. There are 30 points where the first one is in the mouth of the bay and point no. 30 is located in Palu City. The distance between point 1 and 30 is about 30 km. Figure. 8 shows that colour stratitification was clearly observed indicating different tidal elevations in the first 8 minutes after the earthquake. The time frame was during spring tide and in the phase of towards high tide where tidal currents flowed into the bay. Generally, the water elevations in the mouth of the bay were lower than the elevations in the city of palu. Gradual increase of water levels in the last 10 minutes were observed from ~0.73 m – 0.80 m above MSL where the highest water level was at the city of Palu (Figure. 9).

Figure. 10 shows the comparison of all tidal elevations from 18:00 – 18:10 WITA (Central Indonesian Time) or 10:00 – 10:10 UTC in relation with the events of both earthquakes and tsunamis. The main earthquake was recorded at 18.02 WITA (10.02 UTC) and lasted for 30-40 seconds. Smaller earthquake was observed from the video record in Desa Wani 1 for about 7 seconds. In the meantime, the first tsunami wave was observed in the City of Palu (Kampung Nelayan Restaurant) at 18.04 WITA (10.04 UTC). Few minutes later at 18.06 WITA (10.06 UTC), tsunami hit Desa Wani 1. Desa Wani and the City of Palu (Kampung Nelayan Restaurant) is about 20 km apart. Therefore, from the available field data, social media records, the presented curves, and considering the dimension of Palu Bay (about 30 km x 5 km), tsunamis generated in Palu Bay clearly should be from different sources. These have made tsunami simulation in such narrow bay had become a very challenging task (Prasetya *et al.*,

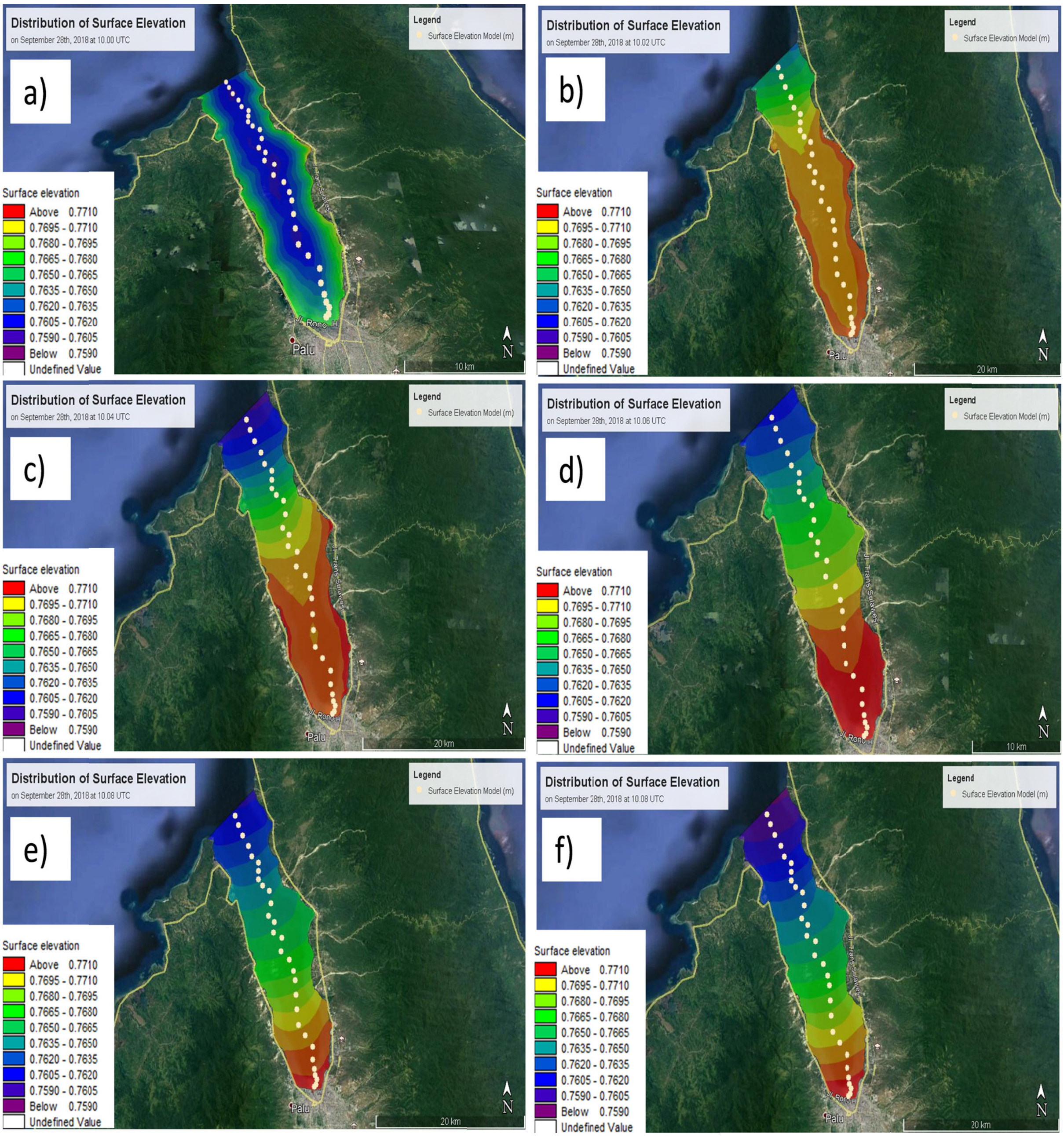


Figure 8. Overview of tidal elevation in Palu Bay from 10:00 – 10:10 WITA (Central Indonesian Time) showing an increase of water elevation towards the city of Palu, a) at 10:00 UTC, b) at 10.02 UTC, c) at 10.04 UTC, d) at 10.06 UTC, e) at 10.08 UTC and f) at 10.10 UTC (see Figure. 9 for more details)

2018, Muhari *et al*,. 2018, Gusman *et al*., 2019, Yalciner *et al*., 2019, Liu *et al*., 2020).

Without implementing the hydrodynamics of the bay, exemplary efforts to model tsunami by employing different tsunami sources inside the bay were conducted by Gusman *et al*., (2019), Ulrich *et al*., (2019) and Nakata *et al*., (2020). Gusman *et al*., (2019) indicated that tsunami sources may be resulted from coastal collapsed, submarine landslide and normal fault in the middle of the bay. High tide was also added as a possible aspect determining the characteristics of tsunami. While Ulrich *et al*., (2019) focused on the generation of tsunami due to vertical step in the middle of the bay, Nakata *et al*. (2020) analysed several subaerial and submarine landslides that may cause the tsunami. Both studies revealed that all possibilities may contributed to the generation of tsunamis and agreed with field data to some degrees. Supported by detailed field data using multi-beam echo sounder, latest findings from Liu *et al*., (2020) discussed in more details about possible subaerial and submarine landslides across the bay. Based on the multi-beam data

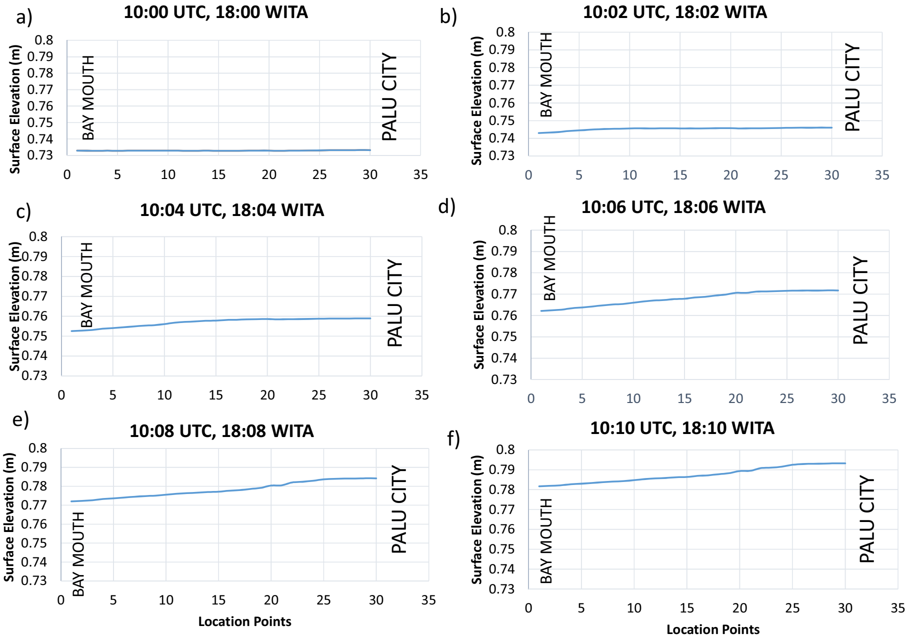


Figure 9. Increase of water elevations in Palu Bay from 18:00 – 18:10 WITA (10:00 – 10:10 UTC) (See Fig 8) a) at 10:00 UTC, b) at 10.02 UTC, c) at 10.04 UTC, d) at 10.06 UTC, e) at 10.08 UTC and f) at 10.10 UTC

in coastal waters and compared them with the data prior the event provided by BIG, there were 14 possible subaerial and submarine landslides in Palu Bay that may cause local tsunamis inside the bay. However, it turned out that even by considering these 14 sources, the simulation still could not explain the complex characteristics of tsunami run-up, inundation and their distribution along the bay (Liu *et al.*, 2020). Significant increase of water levels as discussed in the current study was not included in their analysis. This also may contribute to the difficulties of finding the best fits of tsunami generation models.

Among others, only Gusman *et al.*, (2019) and Carvajal, *et al.*, (2019) who explicitly mentioned the importance of including a high tide condition for the generation of tsunami model. In fact, the interaction of tsunami and tides were mostly neglected by many studies due to the fact that tsunami arrival time of the cases were far longer than the case in Palu 2018. Few studies have tried to describe the importance of tidal characteristics to the propagation of tsunami and most of them focused on tidal rivers (Kowalik & Proshutinsky, 2010, Kalmbacher & Hill, 2015, Shelby *et al.*, 2016 and Wrinckler *et al.*, 2017). Generally, it was concluded that the geometry of the beach, the bathymetry and the tidal phase are very important in affecting the characteristics of tsunami. Tidal phase is very important because it is related to the changing of elevations and the direction of the currents. Based on the models developed by Wrinckler *et al.*, 2017, nonlinear interaction of tide-tsunami model was enhanced by the shallow waters. Moreover, for the case of energetic tidal channel, tide-tsunami interaction has led to large variation in tsunami

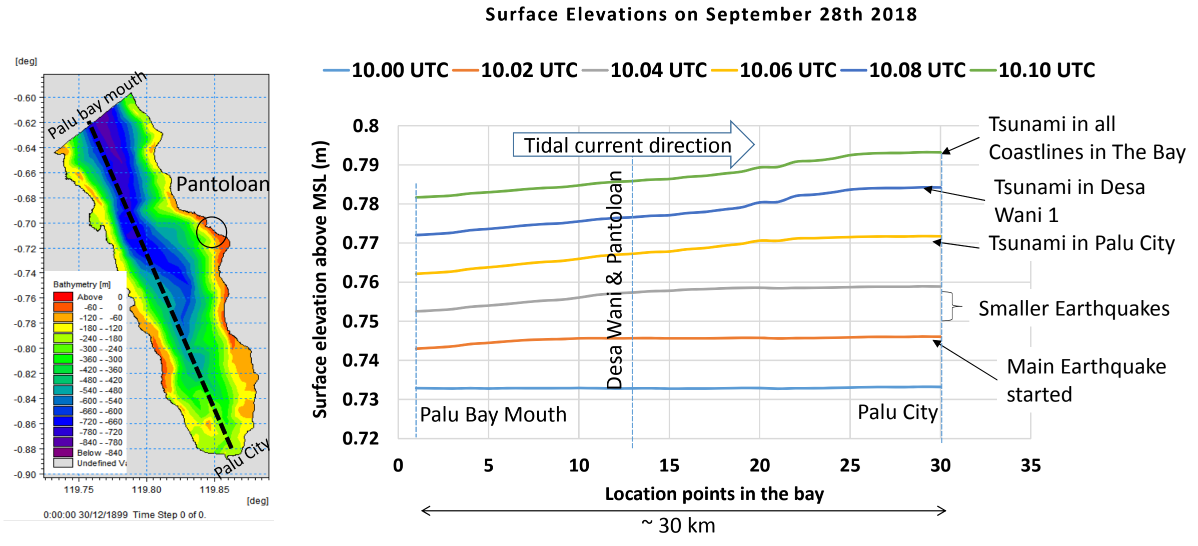


Figure 10. The increase of tidal elevations in the bay during the event of eartquakes and tsunamis

charateristics such as tsunami height, flow speed, and arrival times (Wrinckler *et al.*, 2017).

For the case of Palu tsunami 2018, the tidal condition was at towards high tide (rising) and the direction of the current was towards the city of Palu. While most of the bathymetry profiles in the bay has steep slopes, the bathymetry of the city of Palu waters are different from West to East. The west side is shallower compared to the bathymetry in the east side. During the event of earthquake and tsunami (first 8 minutes), the increase of water levels was about 6 cm in the city of Palu and less than 5 cm in the mouth of the bay (Figure. 10). From the hydrodynamic simulation we can also extract the current velocity ranging from 0.5 cm/s – 1.0 cm/s and moving towards the city of Palu. Therefore, considering that the sources of tsunami may come from both the fault mechanisms and submarine-subaerial landslides, those hydrodynamic characteristics should also be considered in the simulation of tsunami in Palu Bay. The nonlinear interaction between tides and tsunami in a narrow bay like Palu may provide some hints to the arrival times and tsunami propagation in Palu bay in general.

CONCLUSION

On September 28th, 2018, a strike-slip earthquake followed by instantaneous tsunami hit Palu Bay. Field data, seismic analyses, satellite analyses, and tide gauge record in Pantoloan revealed that tsunami was generated by multiple sources such as subaerial landslides, submarine landslide and fault mechanism. For a narrow geometry like Palu Bay, the hydrodynamic is also important to be included because of tidal variation inside the bay. The geometry of Palu Bay and tidal conditions during the event clearly could contribute to the characteristics of propagating tsunami to the shores. The current study has provided insight information on hydrodynamic conditions of Palu Bay during the event of earthquake and tsunami, particularly in the first 8 minutes after the earthquake. There was an increase of elevation by 6 cm and the direction of surface tidal current was toward the city of Palu where the tidal elevation was at its highest compared to other area. This interaction of tides and tsunami was nonlinear and need further discussion. The tides may accelerate or decelerate the fast tsunami arrival time at several locations inside the narrow bay. Therefore, future efforts to simulate tsunami inside the Palu Bay should also consider the hydrodynamics of bay.

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